ENVIRONMENTAL STATEMENT - VOLUME 3 - APPENDIX 6.3

Atmospheric Dispersion Modelling

Drax Bioenergy with Carbon Capture and Storage

The Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations, 2009 – Regulation (5(2)(a))

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1.1. INTRODUCTION

1.1.1. Atmospheric dispersion modelling was performed using the Cambridge Environmental Research Consultants (CERC) Atmospheric Dispersion Modelling System (ADMS 5.2.4). This model uses detailed information regarding the pollutant releases, local building effects and local meteorological conditions to predict pollution concentrations at specific locations selected by the user. The model has been validated against both field studies and wind tunnel studies of dispersion and is widely used for air quality impact assessment in the UK. The modelling inputs and assumptions used are detailed in the following sections.

1.2. KEY DISPERSION MODEL INPUTS

STACK PARAMETERS: BASELINE & WITH PROPOSED SCHEME (CORE MODEL SCENARIOS)

1.2.1. The stack parameters for each modelled core scenario are provided in **Table 1.1** (Baseline and With Proposed Scheme). The flue discharge conditions for the four biomass units represent a reasonable likely operating profile (i.e., each unit at full load for 4,000 hours per year) in the Baseline scenario. In the With Proposed Scheme scenario, each of the two non-BECCS units are assumed to operate at full load for 4,000 hours per year, with the two BECCS units assumed to be running continuously at full load (8,760 hours per year), representing a reasonable worst-case operating profile for the BECCS units.

1.2.2. For the purposes of reporting maximum ground level pollutant concentrations over short-term averaging periods (e.g., hourly mean NO_2, daily mean PM_{10} etc.), all four biomass units in the Baseline scenario were modelled in ADMS v5.2.4 at full load for all hours of the year (8,760 hours) to capture worst case meteorological conditions. For annual mean averaging periods, the model outputs were scaled according to the number of operational hours in the 'mid-merit' operating regime (4,000 hours per annum).

1.2.3. Similarly, in the With Proposed Scheme scenario, the two non-BECCS units were modelled at full load for all hours of the year alongside the proposed BECCS units to capture worst case conditions in relation to short-term averaging periods. However, the annual mean model outputs were scaled in relation to the non-BECCS units only, according to the number of operational hours (4,000 hours). Model outputs relating to the BECCS units were not scaled as they are assumed to be operational at full load for all hours of the year (8,760 hours).

1.2.4. Unless stated otherwise in the below tables, all pollutant emission concentrations are based on the respective emission limit values (ELVs) as per the IED (Council of the European Union, 2010) and / or associated EU Best Available Techniques (BAT)

associated emission levels (BAT-AELs) as per BAT conclusions for large combustion plants (European Commission, 2017).

Table 1.1 - Stack Parameters for the Baseline and With Proposed Scheme Scenarios

Parameter	**Baseline - per Unit**	**With Scheme - per Unit *with* CCS***	**With Scheme - per Unit *without* CCS****
No. Biomass Units	4	2	2
No. flues	2^	1	1
Stack height (m agl)	259	259	259
Flue diameter (m)	8	8	8
Discharge Temp (°C)	144.2	80.0	144.2
Vol. flow (Nm^3/s) (1)	573.0	444.5	573.0
Vol. flow (Am^3/s) (2)	992.5	686.4	992.5
NO_x exit concentration (mg/Nm^3) (3)	160 (200)	160 (200)	160 (200)
NH_3 exit concentration (mg/Nm^3)	10	10	10
PM_{10} exit concentration (mg/Nm^3) (3)	10 (16)	10 (16)	10 (16)
HCl exit concentration (mg/Nm^3) (3)	5 (12)	5 (12)	5 (12)
SO_2 exit concentration (mg/Nm^3) (3)	100 (215)	100 (215)	100 (215)
Amine 1 (mg/Nm^3) (4)	-	0.5 (1.5)	-
Amine 2 (mg/Nm^3) (4)	-	0.3 (1.0)	-
Nitrosamine 1 (mg/Nm^3) (5)	-	0.0001	-
Nitrosamine 2 (mg/Nm^3) (5)	-	0.0001	-
Notes: * Applicable to Unit 1 & Unit 2 only. These units have CCS.			

Parameter	Baseline - per Unit	With Scheme - per Unit *with* CCS*	With Scheme - per Unit *without* CCS**
** Applicable to Units 3 & Unit 4 only. These units to not have CCS ^ One flue serving two Biomass Units (1) – Calculated at 273.15 Kelvin (0°C), pressure of 101.3 kPa, dry, 6% O_2 (2) – Actual discharge conditions, 4.9% H_2O, 7.4% O_2 (3) – Values in parentheses represent daily average emission BAT-AELs used for modelling short-term averaging periods (i.e. daily, hourly, sub-hourly concentrations) (4) – Representative of proposed yearly average ELVs (values in parentheses represent proposed daily average ELVs for 'Amine 1' and 'Amine 2'). The proposed ELVs exceed the reasonable worst-case design emissions concentrations provided by the technology supplier (MHI). (5) – These are not proposed ELVs, but represent nominal emission concentrations provided by MHI based on expected baseload operation, representing reasonable worst-case direct emissions. Contributions to ground level nitrosamine concentrations from direct emissions are shown to be insignificant (<0.2% of EAL for NDMA; see **Appendix 6.4**).			

1.2.5. Given that there will be multiple flues within the Main Stack (i.e. one flue per two biomass units) in both the Baseline and With Proposed Scheme scenarios, emissions from these flues will in effect act as a single plume with combined source characteristics. The combined stack characteristics modelled within ADMS 5.2 are presented in **Table 1.2**.

Table 1.2 - Combined Stack Emission Parameters for the Baseline and with Proposed Scheme Scenarios

Parameter	Baseline Scenario (1)	With Proposed Scheme Scenario (2)
Emission Source	Biomass Units	Biomass Units
No. Units	4	4 (3)
Stack height (m agl)	259	259
Stack location X, Y (m)	466124, 427224	466124, 427224
No. flues	2	2 (3)
Effective Flue diameter (m)	11.3	11.3
Discharge Temp (°C)	144.2	116.8
Exit velocity (m/s)	39.5	33.5

Parameter	Baseline Scenario (1)	With Proposed Scheme Scenario (2)
Vol. flow (Am^3/s)	3,970	3,370
NO_x emission rate (g/s) (4)	366.7 (458.4)	325.5 (406.9)
NH_3 emission rate (g/s)	22.9	20.3
$PM_{10}/PM_{2.5}$ emission rate (g/s) (4)	22.9 (36.7)	20.3 (32.6)
HCl emission rate (g/s) (4)	11.5 (27.5)	10.2 (24.4)
SO_2 emission rate (g/s) (4)	229.2 (492.8)	203.4 (437.4)
Amine 1 emission rate (g/s) (4)	-	0.4 (1.3)
Amine 2 emission rate (g/s) (4)	-	0.3 (0.9)
Nitrosamine 1 emission rate (g/s)	-	0.0001
Nitrosamine 2 emission rate (g/s)	-	0.0001

(1) Effective flue diameter calculated based on area of 2 x actual flue diameter (i.e. 8 m). Vol. flow based on combined total of vol. flows from each unit and exit velocity based on combined vol. flow divided by area of stack exit using effective flue diameter (11.31 m). Pollutant mass emissions based on combined mass emissions from each unit.

(2) With CCS, the exhaust gases from both flues (CCS and conventional) are assumed to merge, giving the 11.31 m effective flue diameter. The gases are assumed to mix, using Ideal Gas law to calculate the resulting average temperature and volume of the merged plume.

(3) Units 1 & 2 with CCS and Units 3 & 4 without CCS. One flue will serve the units with CCS and second flue will serve the units without CCS.

(4) Values in parentheses derived from daily average BAT-AELs (for 'Amine 1' and 'Amine 2', derived from proposed daily average ELVs)

STACK PARAMETERS: WITH PROPOSED SCHEME & OTHER PROJECTS (CUMULATIVE IMPACT ASSESSMENT)

1.2.6. The following projects have been identified for inclusion in the operation phase cumulative impacts assessment, for which development has been approved or approval is being sought:

a. Eggborough Combined Cycle Gas Turbine (CCGT) Power Station[1];

[1] Development Consent Order (PINS reference: EN010081) granted 20 September 2018; https://infrastructure.planninginspectorate.gov.uk/projects/yorkshire-and-the-humber/eggborough-ccgt/?ipcsection=docs

b. Keadby 2 CCGT Power Station[2];

c. Keadby 3 CCGT with Carbon Capture Power Station[3];

d. Energy from Waste (EfW) Plant, Kirk Sandall[4].

1.2.7. The equivalent point sources of emissions from each of the above projects were modelled using ADMS v5.2.4 as part of the cumulative impacts assessment. The associated stack emissions parameters are presented in **Table 1.3**, with data obtained from the respective air quality assessment reports / ES chapters published with each of the above development applications.

1.2.8. The emissions from each source were modelled for each hour of the year (8,760 hours), thus providing a worst-case assessment of long-term (annual mean) impacts. Given the extremely low likelihood of peak operating conditions coinciding across all different emissions sources at any given time, assessment of cumulative short-term air quality impacts (e.g. hourly, daily) has not been undertaken.

Table 1.3 - Flue Emissions Parameters for Other Projects included in Cumulative Impacts Dispersion Modelling

Parameter	Eggborough		Keadby 2	Keadby 3	Kirk Sandall
	CCGT (per unit)	Peaking plant (1) (per unit)	HRSG (2) stack	CCP (3) Absorber Stack	EfW Plant Stack
No. Units	3	10	1	1	1
No. flues	3	10	1	1	1
Stack location X, Y (m)	457600, 423934	457520, 423950	482670, 411606	481820, 412158	460707, 407179
Stack height (m agl)	90	45	75	105	95
Flue diameter (m)	8.1	1.2	8.0	6.8	2.6
Effective stack diameter (m agl)	17.2 (4)	8.5 (4)	8.0	6.8	2.6

[2] Consent granted 1 March 2019; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820117/Keadby_II_Decision_Letter_-_01_March_2019.pdf

[3] Development Consent Order application (PINS reference: *EN010114*), undergoing examination at the time of writing; https://infrastructure.planninginspectorate.gov.uk/projects/yorkshire-and-the-humber/keadby-3-carbon-capture-power-station/#

[4] Planning application reference: *20/01774/TIPA* (Land North West Of Sandall Stones Road Kirk Sandall Doncaster)

Parameter	Eggborough		Keadby 2	Keadby 3	Kirk Sandall
	CCGT (per unit)	**Peaking plant (1) (per unit)**	**HRSG (2) stack**	**CCP (3) Absorber Stack**	**EfW Plant Stack**
Discharge Temp (°C)	75	355	74.1	60	135
Vol. flow (Am^3/s)	3600 (5)	305 (5)	1030	856.4	81.2
Exit velocity (m/s)	15.5 (5)	5.4 (5)	20.5	24.3	15.0
NO_x emission rate (g/s)	172.5 (5)	17.9 (5)	39.5	32.4	8.1
NH_3 emission rate (g/s)	-	-	4.4	1.1	0.7
$PM_{10}/PM_{2.5}$ emission rate (g/s)	-	-	-	-	0.3

Sources:

Eggborough – Data taken from Table 8.10 based on worst-case modelled scenario described in paragraph 8.6.17 and Table 8.9 of Chapter 8 – Air Quality, ES Volume 1 (Eggborough Power Ltd, 2017)

Keadby 2 and Keadby 3 – Data for both sources taken from Table 2 and Table 3 of Appendix 8B: Air Quality – Operational Phase, Keadby 3 ES Volume 2 (Keadby Generation Ltd, May 2021)

EfW Kirk Sandall – Data taken from Table 20 and Table 21 of the Air Quality Assessment Report published with the planning application (BH EnergyGap (Doncaster) Limited, June 2020)

Notes:

(1) Reciprocating gas engines

(2) Heat Recovery Steam Generator

(3) Carbon Capture Plant

(4) Effective stack diameter combines all flues for the respective source

(5) Values based on all units for the respective source

STACK PARAMETERS: WITH PROPOSED SCHEME MITIGATION

1.2.9. To reduce potential impacts relating to acid deposition at sensitive habitats within the Lower Derwent Valley SAC, Thorne Moor SAC and SSSI, and SSSI designations at

Breightion Meadows, Derwent Ings, and Barn Hill Meadows, the following operational changes to the Main Stack emissions parameters were applied:

a. Reduce SO2 emissions by 40%, applied to the CCS Biomass Units

b. Increase exit temperature of flue gases from the CCS Units from 80ºC to 103ºC.

1.2.10. The relevant revised Main Stack emissions parameters are presented in **Table 1.4**. All other stack parameters remain unchanged from those presented in **Table 1.1**.

Table 1.4 - Revised Main Stack Parameters and Combined Flue Emissions Parameters applied to With Proposed Scheme Scenario (With Mitigation)

Parameter	**With Scheme (per Unit *with* CCS)***		**With Scheme (per Unit *without* CCS)****	
	Design (1)	**Mitigation**	**Design (1)**	**Mitigation**
Discharge Temp (°C)	80.0	103.0	144.2	144.2
Vol. flow (Am^3/s) (2)	686.4	731.1	992.5	992.5
SO_2 exit concentration (mg/Nm^3)	100	60	100	100
	Revised Combined Flue Emissions Parameters (2)			
	Design (1)		Mitigation	
Discharge Temp (°C)	116.8		125.3 (3)	
Exit velocity (m/s)	33.5		34.3	
Vol. flow (Am^3/s)	3,370		3,445	
SO_2 emission rate (g/s)	203.4		167.9 (4)	

Notes:

* Applicable to Unit 1 & Unit 2 only (with CCS)

** Applicable to Units 3 & Unit 4 only (without CCS)

(1) As per Table 1.1

(2) The exhaust gases from both flues (CCS and non-CCS) are assumed to mix, using Ideal Gas law to calculate the resulting average temperature and volume of the merged plume.

(3) Combined (CCS and Non-CCS Units) exit temperature resulting from increased exit temperature (assumed 100ºC for conservatism) applied to two BECCS Units only

(4) 40% reduction applied to BAT-AEL SO_2 exit concentration (CCS Units only)

STACK PARAMETERS: WORST CASE EMISSIONS PROFILE SENSITIVITY TEST

1.2.11. Sensitivity modelling was undertaken for the core model scenarios (Baseline and With Proposed Scheme stack parameters as per **Table 1.2**), but assuming that all Biomass Units in the Baseline scenario and the non-CCS Units 3 & 4 in the 'With Proposed Scheme' scenario would be operating at full load for all hours (8,760 hours) of the year. This represents a worst-case emissions profile for both the Baseline and With Proposed Scheme scenarios. Results relating to these sensitivity scenarios are reported in **Tables 1.13 to 1.20** of **Appendix 6.4 (Operational Phase Air Quality Assessment Results Tables: Human Receptors)** (document reference 6.3.6.4) and **Tables 1.19 to 1.24** of **Appendix 6.5 (Operational Phase Air Quality Assessment Results Tables: Ecological Receptors)** (document reference 6.3.6.5).

METEOROLOGICAL DATA

1.2.12. The model has utilised hourly sequential meteorological data from RAF Waddington, for five years from 2016 to 2020. The site lies 69 km to the south of the Order Limits. Both the location of the Drax Power Station Site and RAF Waddington are inland sites, to the east of England (and east of the Peak District) in areas of limited terrain influence. As such, the data from the RAF station are considered appropriate for the assessment.

1.2.13. The open setting of the Power Station Site, with relatively sparse development in the vicinity, is taken into account in the modelling by setting the surface roughness length to 0.2 m. This is the value recommended by the model developers for agricultural areas (with short vegetation).

1.2.14. The wind roses for 2016 to 2021 are provided in **Plate 1.1**. The predominant wind direction is from the southwest in all years.

BUILDING DOWNWASH

Baseline and Proposed Scheme

1.2.15. The dispersion model considers the effects of building downwash of pollutants. Downwash is the enhanced turbulent mixing of pollutants in the lee of buildings which can result in relatively elevated pollutant concentrations in the wake of the building. Given the height of the Main Stack (159 m agl), building downwash effects are expected to be minimal.

1.2.16. However, the existing cooling towers within the north and south of the Site have been included as buildings in the model for both the Baseline and Proposed Scheme scenarios. These are depicted in **Plate 1.2** and the associated building dimensions are presented in **Table 1.5**.

Table 1.5 - Modelled Building Parameters within Drax Power Station Site

Name	Shape	X (m)	Y (m)	Height (m agl)	Diameter (m)
Cooling Tower North 4A (CT4A)	Circular	466596.6	427571.8	114	95.6
CT4B		466464.1	427529.7		
CT5A		466326.6	427539.8		
CT5B		466219.1	427631.3		
CT6A		466351.3	427674.5		
CT6B		466490.2	427665.4		
Cooling Tower South 1 (CTS1)		466175.4	426796.2		
CTS2		466306.7	426775.5		
CTS3		466097.8	426680.4		
CTS4		466117.2	426548.6		
CTS5		466254.5	426519.1		
CTS6		466327.3	426632.4		

Other Projects

1.2.17. Additional building parameters were included in the cumulative impacts air quality model, which are specific to the other projects included in the assessment.

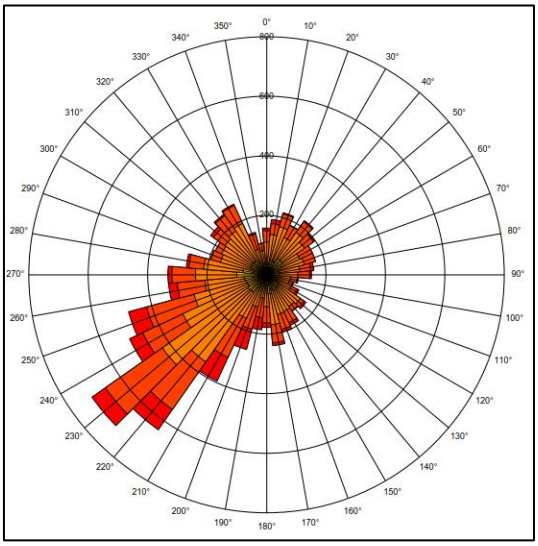
1.2.18. Details of the buildings relating to the Eggborough CCGT[1], Keadby 2[2] and Keadby 3[3] model inputs (as per the sources of information presented in **Table 1.3**), which were included in the With Proposed Scheme & Other Projects model scenario, are provided in **Table 1.6**.

1.2.19. Buildings relating to the Energy from Waste (EfW) Plant, Kirk Sandall[4] were not included in the model due to the maximum number of buildings allowed in ADMS v5.2.4 being reached, as a result of building inputs relating to the Proposed Scheme and aforementioned other projects. Given the high pollutant mass emission rates from the sources relating to Eggborough CCGT, Keadby 2 and Keadby 3, compared to the EfW, priority was given to representing the potential effects of building downwash from these sources.

Table 1.6 - Modelled Building Parameters relating to Other Projects

Name	Shape	X (m)	Y (m)	Height (m agl)	Length (m)	Width (m)	Angle (º)
Eggborough_1 (Eggbh_1)	Rectangular	457586	423905	50	63	28	119
Eggbh_2		457650	423794	30	76	76	119
Eggbh_3		457643	423923	50	63	28	119
Eggbh_4		457665	423960	50	63	28	119
Eggbh_5		457697	423905	30	49	134	119
Eggbh_6		457541	423986	30	64	102	119
Eggbh_7		457500	423910	30	35	54	119
Keadby_1		482676	411630	40	16.15	46.17	104
Keadby_2		482699	411676	30	47.3	19.9	104
Keadby_3		482630	411659	30	45.8	45.7	104
Keadby_4		481820	412158	90	13	40	0

Plate 1.1 - Wind Roses for RAF Waddington Hourly Meteorological Data (2016-2020)



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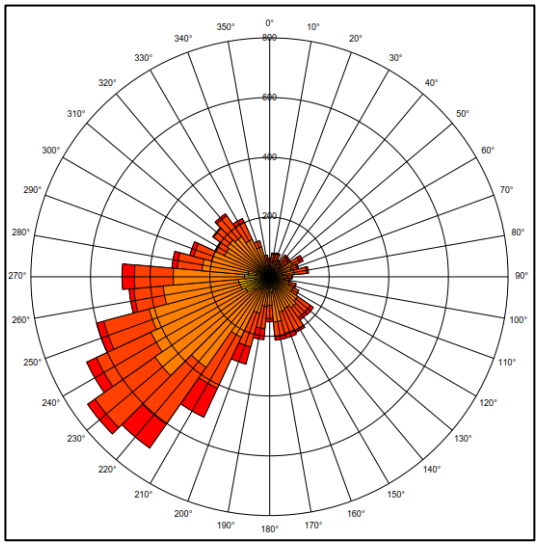

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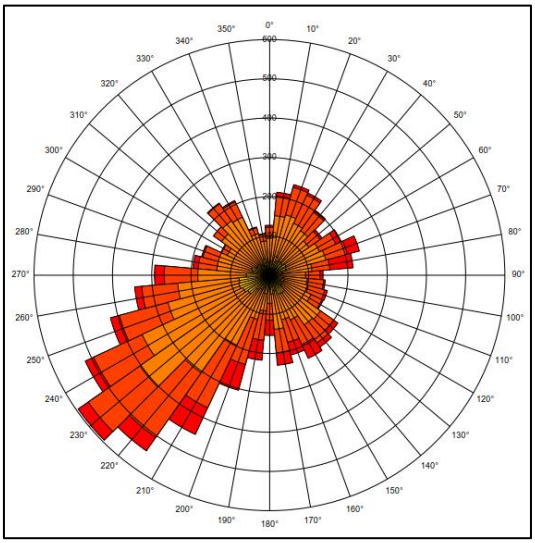

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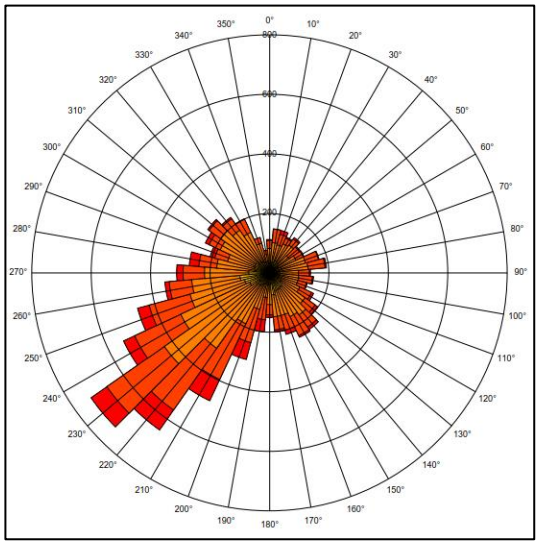
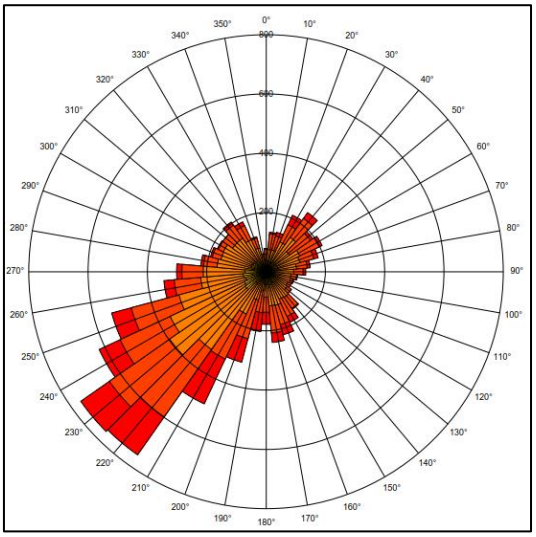


2019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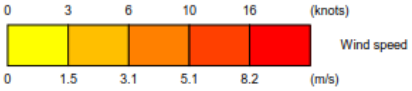
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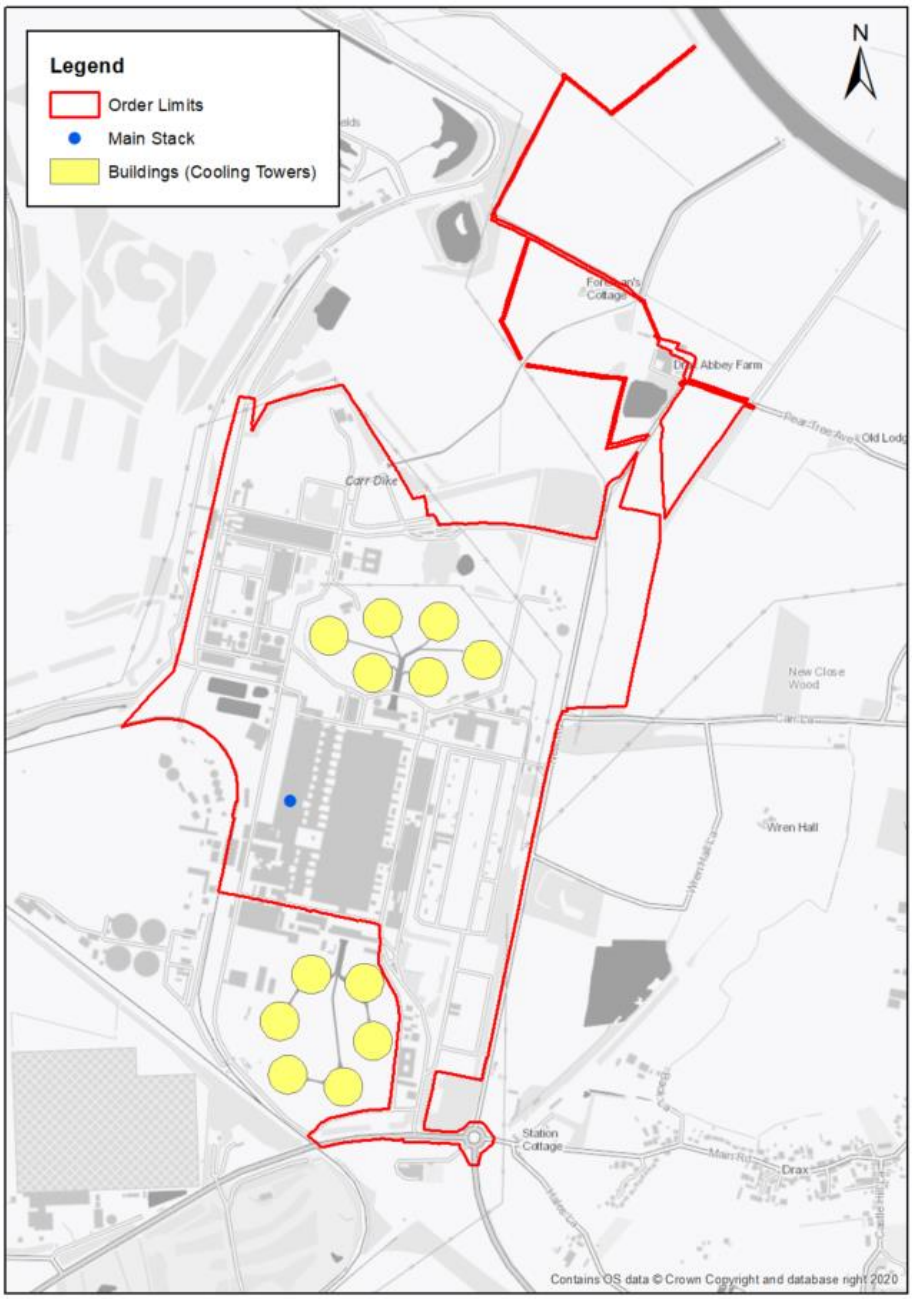
Wind speed
0 1.5 3.1 5.1 8.2 (m/s)

2020

Plate 1.2 - Modelled Buildings Layout



TERRAIN

1.2.20. Terrain was not included in the modelling since there are no significant gradients in the operation phase study area.

ATMOSPHERIC CHEMISTRY

1.2.21. Emissions of NO_x from combustion sources include both nitrogen dioxide NO_2 and nitric oxide (NO), with the majority being in the form of NO. In ambient air, NO is oxidised to form NO_2, and it is NO_2 which has the more significant health impacts. For this assessment, the conversion of NO to NO_2 has been estimated using the worst-case assumptions set out in EA guidance (Environment Agency, 2006), namely that:

a. For the assessment of long term (annual mean) impacts, at receptors 70% of NOx is NO_2;

b. For the assessment of short term (hourly mean) impacts, at receptors 35% of NOx is NO_2.

1.2.22. The oxidation of NO to NO_2 is not, however, an instantaneous process, thus the EA worst case assumptions are very conservative for modelled impacts within a few hundred metres of the Main Stack.

1.2.23. For all modelled scenarios where the ADMS v5.2.4 chemistry option is enabled, the proportion of NO_x assumed to be as NO_2 in the flue gas at stack exit is 5%, which aligns with the ADMS default.

DEPOSITION

1.2.24. The deposition of nitrogen (from NO_2 and NH_3), sulphur, and hydrogen chloride is modelled using a deposition velocity approach, where the surface flux of pollutants is modelled by multiplying the ground level concentration by a pollutant specific deposition velocity. The dry deposition velocities used in the assessment are based on recommended values given by EA guidance (Environment Agency, 2014) and are provided in **Table 1.7**.

Table 1.7 - Modelled Dry Deposition Velocities

Chemical Species	Deposition Velocity (mm/s)	
NO_2	Short vegetation	1.5
	Long vegetation	3.0
SO_2	Short vegetation	12.0
	Long vegetation	24.0
NH_3	Short vegetation	20.0
	Long vegetation	30.0

Chemical Species	Deposition Velocity (mm/s)	
HCl	Short vegetation	25.0
	Long vegetation	60.0

1.2.25. The deposition flux is calculated by multiplying the modelled annual mean concentration of the respective pollutant species by the deposition velocity.

1.2.26. As deposition occurs, the exhaust gas plumes are depleted slightly of material. This was accounted for in the ADMS model using the in-built dry deposition facility with the 'plume depletion' option switched on. However, the deposition velocity for NO_x was set to zero in the model, given that further processing is applied to the model outputs to convert NO_x concentrations to NO_2 (as outlined above using EA guidelines). Therefore, modelled depletion of NO_x / NO_2 from the plume was effectively zero.

1.2.27. Deposition of nitrogen from amine compounds is discussed in the below section.

RECEPTOR GRID EXTENTS

1.2.28. To ensure that spatial variations in ground level concentrations were assessed and depicted throughout the operational phase Study Area, a 30 km x 30 km regular Cartesian receptor grid was modelled at a resolution of 200 m, centred on the main stack.

1.2.29. The X, Y Ordnance Survey coordinate extents of the receptor grid, which was modelled at 0.5 m agl to primarily focus on the distribution of impacts within ecological sites, are:

a. Xmin 451124; Xmax 481124;

b. Ymin 412224; Ymax 442224

1.3. MODELLING OF AMINE COMPOUNDS

OVERVIEW OF AMINES, NITROSAMINES & NITRAMINES

1.3.1. Amines are organic derivatives of ammonia (NH_3), wherein one or more of the hydrogens (H) atoms are replaced by a substituent organic group (R). The type of amine can be defined as primary, secondary, or tertiary, based on the number of H atoms that are replaced:

a. Primary amine (R-NH_2) where 1 H-atom is replaced

  i. e.g., Monoethanolamine, MEA

b. Secondary amine (R_2-NH) where 2 H-atoms are replaced

  i. e.g., Dimethylamine, DMA

c. Tertiary amine (R_3-N) where 3 H-atoms are replaced

i. e.g., Trimethylamine, TMA

1.3.2. Amine-based solvents are used in the carbon capture process to remove carbon dioxide (CO_2) from combustion flue gases (i.e., for the Proposed Scheme, removal of CO_2 from post-combustion gases associated with two biomass units prior to flue gas release via the Main Stack). However, the amine compounds included within the solvent make-up can react with substances other than CO_2 to create new, potentially harmful compounds (e.g., nitrosamines and nitramines), both within the carbon capture process and in the atmosphere following release of the treated post-combustion flue gases. Therefore, it is important that emissions to atmosphere, associated chemical transformations, and dispersion and deposition within the study area are represented within the air quality model.

1.3.3. Direct emissions of nitrosamines from the Main Stack, associated with potential solvent degradation within the BECCS process and entrainment within the flue gas, are expected to be negligible. Nevertheless, direct mass emissions of nitrosamines from the BECCS process in the assessment of the Proposed Scheme have been modelled based on reasonable worst-case nominal emissions provided by the technology supplier (MHI), as per **Table 1.1**, for all hours of the year. However, the majority of nitrosamine and nitramine compounds associated with the Proposed Scheme will form in the atmosphere as a result of the complex reactions outlined below (i.e., 'indirect' emissions).

1.3.4. As reported in **Table 6.2** of **Chapter 6 (Air Quality)** (document reference 6.1.6), the Environment Agency recommends that the contributions of directly emitted nitrosamines from those formed through atmospheric reactions are differentiated. The respective direct and indirect contributions of nitrosamines for the relevant model scenarios are presented in **Table 1.9** (With Proposed Scheme core scenario) and **Table 1.20** (With Proposed Scheme worst-case emissions profile sensitivity test) in **Appendix 6.4 (Operational Phase Air Quality Assessment Results Tables: Human Receptors)**. As evidenced in **Appendix 6.4 (Operational Phase Air Quality Assessment Results Tables: Human Receptors)**, the process contribution to ground level concentrations of direct nitrosamine emissions is insignificant (<0.1% of the EAL for NDMA). Given the negligible emissions under baseload operation and the associated insignificant impacts, there is no requirement to propose an annual average ELV for direct nitrosamine emissions.

1.3.5. Nitrosamines and nitramines are organic compounds, formed by reactions with nitrogen monoxide (NO) and nitrogen dioxide (NO_2), respectively. The chemical structure of nitrosamines is R2N-NO and the structure of nitramines is R2N-NO_2, formed from the original amine, where R is usually an alkyl group. Nitrosamines are susceptible to photodegradation and therefore generally short-lived in the atmosphere (~5 min). In contrast, nitramines are more stable and will have longer atmospheric residence times (~2 days) (Sørensen, 2013). As such, the stability of nitramines indicates an increased potential for accumulation in the atmosphere relative to nitrosamines.

1.3.6. Existing toxicological data indicates that most nitrosamines are carcinogenic, with the most widely researched nitrosamine being N-nitrosodimethylamine (NDMA), formed from DMA, due to its toxicity. Accordingly, the EAL established by the EA for the assessment of nitrosamines is derived for NDMA. Less is known about nitramines, but they have the potential to be mutagenic and carcinogenic although typically less potent than nitrosamines, with some research studies indicating that nitramines are at least six times less toxic (Gjernes, 2013) and fifteen times less mutagenic (Wagner, 2014) than nitrosamines.

1.3.7. To ensure a conservative approach to the assessment of nitrosamines and nitramines relating to the Proposed Scheme, the modelled concentrations of each compound in this study have been summed (i.e. *nitrosamines* + *nitramines*) at each receptor / grid point and compared to the EAL for NDMA.

MODELLING AMINE CHEMISTRY IN ADMS

1.3.8. For the assessment of amines and associated degradation products relating to the proprietary amine-based solvent proposed for use with the Proposed Scheme, the ADMS Amine Chemistry Module (CERC, 2016) has been utilised to model the chemical reactions associated with the release of specified amine compounds and formation of associated nitrosamines and nitramines in the atmosphere.

1.3.9. Whilst the EA acknowledge that the uncertainty associated with modelling of amines is likely to be very high, the EA's latest guidance (Environment Agency, 2021) on the assessment of impacts to air quality from amine-based post-combustion carbon capture plants states "…*the only commercially available modelling software to evaluate the potential impacts from amines and amine degradation products releases is the amines module within ADMS. The amines chemistry module is based on established science considering published research on mechanisms of formation of toxic compounds. Although the validation of the module is not possible at the moment, the ADMS air dispersion modelling algorithms are continually validated against real world situations, field campaigns and wind tunnel experiments*."

1.3.10. The mechanisms for the formation of nitrosamines and nitramines in the atmosphere are complex. However, the main initial reaction of amines in the atmosphere is with hydroxyl (OH) radicals and it is this reaction on which the ADMS amine chemistry scheme is based (CERC, 2016). As described above, the subsequent formation of nitrosamines and nitramines are attributed to reactions with NO and NO_2, however, they can further degrade in the atmosphere (e.g., through photo-oxidation and subsequent reaction with oxygen molecules to form imines, which are relatively stable and non-toxic compounds (Manzoor, 2015)).

1.3.11. Primary amines do not form stable nitrosamines, meaning that any such nitrosamines would be rapidly isomerised to the respective imine. However, secondary and tertiary amines do form stable nitrosamines. The ADMS module includes an option to allow only unstable nitrosamines to be created (i.e., assuming emissions of primary amines only), if selected by the model user, meaning all nitrosamine concentration outputs are set to zero and only nitramines will form. This option was

not selected for the Proposed Scheme modelling assessment, regardless of the amine compound being emitted (i.e., primary, secondary, and / or tertiary).

1.3.12. The general reaction scheme simulated by the ADMS amines module is as follows:

AMINE + hydroxyl radical (•*OH*)	→	amino RADICAL + H_2O	(1a)
	→	non-amine radical ($RN(H)C^{\bullet}H_2$) + H_2O	(1b)
amino RADICAL + O_2	→	imine + hydroperoxyl (HO_2)	(2)
amino RADICAL + *NO*	→	NITROSAMINE	(3)
amino RADICAL + NO_2	→	NITRAMINE	(4a)
	→	imine + nitrous acid (*HONO*)	(4b)
	hυ		
NITROSAMINE	→	amino RADICAL	(5)

Notes: R represents an alkyl group.
Terms in capitals are the generic names given the respective compounds for which input data are required for modelling in ADMS v5.2.4

1.3.13. The amount of nitrosamine and nitramine formed in the atmosphere is dependent on the initial reaction of the amine with the OH radical – specifically the branching ratio of the abstraction of an H atom from the amino group (N-H) (i.e. forming the amino RADICAL) to the abstraction from the methyl group (C-H) (i.e. forming the non-amine radical) – where a lower branching ratio will result in fewer amino radicals being made available and thus fewer nitrosamine / nitramine compounds being formed. However, a number of other variables play an essential role in the potential formation of nitrosamines and nitramines in the atmosphere and are required for the ADMS amine chemistry module to run, including:

a. Ambient concentrations of the OH radical;

i. A representative annual average OH radical concentration for the UK was sourced from published research (Walker, 2015), based on measurements taken from a series of daytime and night-time flights over the UK in summer 2010 and winter 2011 using the fluorescence assay by gas expansion (FAGE) technique. In the absence of sunlight, OH is not formed at night and therefore OH was not detected above the instrument's limit of detection during any of the night-time or winter daytime flights.

ii. An upper limit OH concentration of 1.8×10^6 molecules cm^{-3} is reported, which is calculated based on summer daytime flights only.

iii. This is the value used to feed into the amine chemistry modelling and is likely to be conservative (skewed high) as an annual average due to there being more daylight hours in summer relative to winter (i.e. if more OH radicals are available in the atmosphere, daytime amine degradation

increases, resulting in increased production of nitrosamine / nitramine compounds).

b. Photolysis rates applicable to the region of study;

i. The ADMS meteorological pre-processor provides hourly information with respect to incoming solar radiation (*K*) specific to the meteorological year data and latitude. A subsequent calculation is completed using the *K* values to derive hourly photolysis rates, which are then used to calculate an annual average rate constant for NO_2 (jNO_2) (CERC, 2016).

ii. The meteorological data used in the amine chemistry module aligns with that used for modelling of all other non-amine related pollutants, comprising hourly data for years 2016-2020 inclusive from RAF Waddington.

c. Ambient concentrations of ozone (O_3) and NO_x (i.e. NO and NO_2);

i. The amine reaction scheme requires hourly background levels of NO_x and O_3 equivalent to the year of meteorological data. Hourly data for these species were sourced from Defra's Hull Freetown AURN monitoring site, representing urban background levels, for the years 2016-2020 inclusive.

ii. Background NO_x concentrations are used to dictate the availability of NO and NO_2 in the formation of nitrosamines and nitramines, respectively, on an hourly basis.

iii. The hydroxyl radical concentration varies based on a number of factors, including solar radiation, latitude, and background levels of O_3. The ADMS amine module requires a constant, '*c*', which is used to calculate hourly varying OH radical concentrations for the region of study. The value for *c* is derived based on the relationship between annual average values for jNO_2, O_3 and OH radical concentrations as described above.

1.3.14. The reaction rates and associated kinetic parameters input to ADMS v5.2.4 for the 'AMINE', 'amine RADICAL', 'NITROSAMINE', and 'NITRAMINE' species need to be defined by the model user. Reaction rate coefficients and kinetic parameters specific to these species associated with the proprietary amine solvent proposed for use in the BECCS process, as part of the Proposed Scheme, have been provided by the BECCS technology supplier (MHI) for use in the atmospheric dispersion modelling. These data remain confidential and, as such, are not published in this Chapter. However, further sensitivity testing in relation to modelling amine atmospheric chemistry has been completed to address this (see '**Amine Chemistry Sensitivity Testing**' below).

1.3.15. The general description of the ADMS amine chemistry scheme can be summarised in five steps:

1. On an hourly basis, ADMS uses the above input parameters to model concentrations of the species of interest as well as the age of the primary pollutants (e.g., amines) at each receptor / grid point using the standard ADMS dispersion algorithms.

2. Using the ‘dilution and entrainment’ scheme within the ADMS amines module, the primary pollutant concentrations are adjusted to removed dilution effects (i.e. becoming increasingly conservative with distance from stack exit).
3. The chemistry reaction scheme requires consideration of timescales, so that after each hourly dispersion calculation, the 'age' of the pollutants is calculated based on the plume travel time. The chemical reaction equations are applied over a time (dt) to all pollutants from the source.
4. At this point, the ‘dilution and entrainment’ scheme is used to dilute all pollutants as ambient air, containing the background pollutants, is entrained into the plume.
5. Steps 3 and 4 are repeated for each time step until time becomes equal to the pollutant ‘age’.

1.3.16. An overview of the input variables required by the amine chemistry module in ADMS is provided in **Table 1.8**. Where possible, the respective input data have been presented relative to the Proposed Scheme core scenario modelling completed and reported in **Chapter 6 (Air Quality)**.

MODELLING DEPOSITION OF AMINES IN ADMS

1.3.17. The method for calculating deposition of amines and associated products (nitrosamines, nitramines) in ADMS was undertaken based on the following approach:

1. Run the respective amine chemistry model runs with amine chemistry switched on and deposition switched off (i.e., as detailed above).
2. Run the same model set up as in Step 1, but with the amine chemistry switched off and deposition switched on.
3. Run the same model set up as in Steps 1 / 2, but with both amine chemistry and deposition switched off.

1.3.18. Based on the outputs from step 2 (deposition switched on) and step 3 (deposition switched off), the ratio of the concentration to deposition flux was calculated for each amine and at each receptor / grid location. This ratio was then multiplied by the concentration output from step 1 (amine chemistry switched on) to derive the amine deposition fluxes at all receptor and grid locations. In summary, the approach can be viewed as:

$$D = C_1 \times \left(\frac{D_2}{C_3}\right)$$

Where:

***D* is the deposition flux for the respective amine compound**

C_1 is the output concentration from Step 1

D_2 is the output deposition flux from Step 2

C_3 is the output concentration from Step 3

1.3.19. Research published by Karl et al. (Karl, 2009), which reports on worst-case studies for assessing deposition of amines from carbon capture plants, adopted a deposition

velocity of 10 mm/s for amines and 30 mm/s for nitrosamines and nitramines. This reflects that the solubility of amines is relatively lower than that of nitrosamines and nitramines. However, in the absence of recommended deposition velocities for these compounds, a conservative approach has been adopted for the Proposed Scheme assessment, whereby the deposition velocity for all amine, nitrosamine, and nitramine compounds is assumed to be equivalent to that for ammonia (30 mm/s) (i.e., all gaseous amine compounds assumed to be highly soluble). Furthermore, the deposition of amines was only taken into account in the modelling of impacts on ecological receptors.

AMINE CHEMISTRY SENSITIVITY TESTING

1.3.20. Given that the specified reactivity data for the proprietary amine and nitrosamine compounds remain confidential, additional model sensitivity testing has been completed based on applying amine reaction rate coefficients equivalent to proxy amine and nitrosamine compounds, for which published data in the public domain are available.

1.3.21. Namely, the proxy compound for 'Amine 1' is MEA and the proxy for 'Amine 2' is DMA, which is a precursor to the formation of NDMA. NDMA has also been used as a proxy for directly emitted nitrosamines (i.e., 'Nitrosamine 1' and 'Nitrosamine 2')[5].

1.3.22. The use of MEA as a proxy compound enables direct comparison with the Environment Agency's EALs for MEA. The use of DMA ensures that any predicted atmospheric formation of nitrosamine, in addition to directly emitted nitrosamines, will be as NDMA, which also allows for direct comparison with the Agency's EAL for NDMA (see **Table 6.1** of **Chapter 6 (Air Quality)**).

1.3.23. The MEA and NDMA reaction rate coefficients applied in the amine sensitivity testing have covered low, mid, and high range values based on literature research for these compounds and are reported in **Table 1.8**. The equivalent reaction rate coefficients for the confidential amine compounds fall within the tested range of values applicable to MEA and DMA, thereby addressing uncertainty in key parameters used in modelling amine chemistry within ADMS.

1.3.24. The results and analysis relating to the amine chemistry sensitivity tests are reported in **Tables 1.21** (MEA) and **1.22** (NDMA) of **Appendix 6.4 (Operational Phase Air Quality Assessment Results Tables: Human Receptors)**.

[5] Although MEA (as proxy for 'Amine 1') does not react directly with other substances to form a stable nitrosamine compound (Scottish Environment Protection Agency, 2015), for the purposes of providing a conservative assessment, it has been assumed that all direct emissions of 'Nitrosamine 1' from the stack will be as NDMA. The use of DMA (as proxy for 'Amine 2') means that all direct and indirect emissions of 'Nitrosamine 2' will be as NDMA.

Table 1.8 - Parameters relating to the ADMS Amine Chemistry Module applicable to the With Proposed Scheme Scenario

Parameter	Units	Notes	Core Scenario Modelling	Amine Sensitivity Modelling [1], [2]	
Amine emission	g/s	Emission rate for amine compounds	As per Table 1.2	Stack emissions based on proxy compounds and initial design mass emission data to provide conservative assessment [2]: 'Amine 1' – MEA; 1.27 g/s 'Amine 2' – DMA; 0.25 g/s	
Direct nitrosamine emission	g/s	Emission rate for nitrosamine compounds	As per Table 1.2	Stack mass emission as per core scenario modelling, but as proxy compounds: 'Nitrosamine 1' – NDMA (*Direct emission only*)[5] 'Nitrosamine 2' – NDMA	
NO_x emission	g/s	Emission rate for NO_x, based on BAT-AEL	As per Table 1.2	As per core scenario modelling	
Amine compound & Molar mass	g/mol	Name of amine compounds included in ADMS Amine Chemistry Module	Amine and nitrosamine compounds relating to proprietary solvent provided by MHI and are confidential. Proxy amine compounds used in sensitivity testing to align with Environment Agency's EAL compounds.	Proxy compounds: 'Amine 1' – MEA 'Amine 2' – DMA 'Nitrosamine 1' – from MEA [3] 'Nitrosamine 2' – from NDMA 'Nitramine 1' – From MEA 'Nitramine 2' – From DMA	Molar mass: 61 45 90 74 106 90
Amine / OH reaction rate constant, *k1*	/ppb/s	Relating to the reaction of the emitted amine with the OH radical	Proprietary amine data	MEA ('Amine 1') Low: 1.72 Mid: 1.90 High: 2.07	DMA ('Amine 2') Low: 1.41 Mid: 1.46 High: 1.50
Amino radical / O_2 reaction rate constant, *k2*	/ppb/s	Relating to the reaction of the amino radical with oxygen (forming imine)	Proprietary amine data	MEA ('Amine 1') [4] Low: 8.63×10^{-8} Mid: 4.44×10^{-8} High: 2.96×10^{-9}	DMA ('Amine 2') [4] Low: 8.13×10^{-8} Mid: 4.19×10^{-8} High: 2.96×10^{-8}
Rate constant for formation of nitrosamine, *k3*	/ppb/s	Relating to the formation of nitrosamine from the reaction of the amino radical with NO	Proprietary amine data	MEA ('Amine 1') [3] Low: 0.00128 Mid: 0.00345 High: 0.00542	DMA ('Amine 2') Low: 0.00182 Mid: 0.00192 High: 0.00192

Parameter	Units	Notes	Core Scenario Modelling	Amine Sensitivity Modelling [1], [2]	
Rate constant for formation of nitramine, *k4a*	/ppb/s	Relating to the formation of nitramine from the reaction of the amino radical with NO_2	Proprietary amine data	MEA ('Amine 1') Low: 0.00019 Mid: 0.00370 High: 0.00715	DMA ('Amine 2') Low: 0.00715 Mid: 0.00715 High: 0.00715
Amino radical / NO_2 reaction rate constant, *k4*	/ppb/s	Relating to the reaction of the amino radical with NO_2 (forming imine or nitramine)	Proprietary amine data	MEA ('Amine 1') Low: 0.0005 Mid: 0.0079 High: 0.0150	DMA ('Amine 2') Low: 0.0145 Mid: 0.0153 High: 0.0160
Branching ratio for amine / OH reaction	Dimensionless	The ratio of H atom abstraction from amino group (N-H) to the methyl group (C-H)	Proprietary amine data	MEA ('Amine 1') Low: 0.05 Mid: 0.10 High: 0.15	DMA ('Amine 2') Low: 0.38 Mid: 0.40 High: 0.42
Ratio of $j_{(nitrosamine)}$ / jNO_2	Dimensionless	Ratio of photolysis rate constants for the nitrosamine and NO_2	*jNO_2* ranges between 1.25 x 10^{-3} s^{-1} and 1.31 x 10^{-3} s^{-1} dependent on met year *$j_{(nitrosamine)}$* based on proprietary amine data	**jNO_2**; As per core scenario modelling	
				$j_{(nitrosamine)}$ Not applicable to MEA ('Amine 1') because primary amines do not form stable nitrosamines (CERC, 2012). [2]	DMA ('Amine 2') Low: 7.00 x 10^{-4} s^{-1} Mid: 5.15 x 10^{-4} s^{-1} High: 3.3 x 10^{-4} s^{-1}
				Ratio of $j_{(nitrosamine)}$ / jNO_2 Not applicable to MEA ('Amine 1')	DMA ('Amine 2') Low: 0.53 Mid: 0.39 High: 0.25
Constant, *c*, for OH concentration calculations	s	Constant for calculating hourly varying OH concentrations, based on relationship between annual average *jNO_2*, O_3 and OH concentrations	Value of *c* ranges between 2.45 x 10^{-3} s^{-1} and 3.01 x 10^{-3} s^{-1} dependent on met year (modelling completed across five years of met data)	As per core scenario modelling	
Atmospheric O_2 concentration	ppb	Concentration of oxygen in air (equivalent to 21% mixing ratio)	209,406,000 ppb	As per core scenario modelling	
Background NO_x / NO_2 concentrations	µg/m^3		Defra AURN urban background monitoring site at Hull Freetown,	As per core scenario modelling	

Parameter	Units	Notes	Core Scenario Modelling	Amine Sensitivity Modelling [1], [2]
Background O_3 concentrations	$\mu g/m^3$	Ambient hourly concentrations for each species sourced from representative monitoring location	aligning with met data years (2016-2021)	

Notes:

[1] Data relating to model variables included in amine sensitivity modelling based on the following sources: (CERC, 2012), (Manzoor, 2015), (Nielsen, 2011). MEA and DMA represent two of the most studied amine compounds relating to emissions from carbon capture plants, thus resulting in greater data availability relating to their respective reaction schemes. Specifically, DMA is a secondary amine from which the nitrosamine, NDMA, is formed. Therefore, testing was carried out whereby all amine emissions were as MEA ('Amine 1') and DMA ('Amine 2'), with results assessed within the context of the Environment Agency EALs for MEA (amines) and NDMA (nitrosamines and nitramines). The assumption that all modelled direct and indirect nitrosamine parameters associated with the Proposed Scheme will be equivalent to NDMA represents a worst-case approach in terms of assessment versus the EAL, given that NDMA is considered to be one of the most toxic nitrosamines.

[2] Amine sensitivity modelling was based on initial design mass emission data provided by MHI that is no longer representative of the proposed BECCS plant. However, the initial design emissions represent higher mass emissions of the amine compounds relative to the proposed permit ELVs used in the core scenario modelling. As such, the initial design emission rates were used and also applied to the proprietary solvent (confidential) data as part of the sensitivity testing to allow a direct comparison with the proxy compound modelling results, whilst also providing a conservative assessment of amine mass emissions from the Main Stack. Therefore, the results of the amine sensitivity modelling are self-contained and should not be compared to the core scenario modelling results.

[3] For the purposes of representing amine chemistry using the ADMS module, the molar mass relating to the nitrosamine formed from MEA ('Amine 1') was included along with a value for k_3 above zero. This ensures that there is still a sink for the amino radical and that not all amino radicals react with NO_2 to form nitramine, which would not be realistic. After reacting with NO to form nitrosamine, the amino radical is not regenerated, but instead rapidly isomerises to form the imine. The photolysis rate of the nitrosamine, $j_{(nitrosamine)}$, is set to zero for this reason. Given that, based on current understanding, a stable nitrosamine is not formed from MEA in the atmosphere, the concentration output is not reported (CERC, 2012). However, in terms of direct nitrosamine emissions, all 'Nitrosamine 1' emissions are conservatively treated as NDMA.

[4] For the sensitivity testing, the 'low' range reaction rate values for k_2 (formation of imine) are higher than the corresponding 'high' range values. This is because a higher k_2 value means that a higher proportion of the amino radicals are removed from the atmosphere to form imine and thus reducing the number of radicals available to react with NO / NO_2 to form a corresponding nitrosamine / nitramine. Whereas a lower k_2 value means that there is a greater proportion of amino radicals available to form nitrosamine / nitramine, thereby increasing ground level concentrations.